Alliance for Industry Decarbonization

Accelerating decarbonisation using bioenergy with carbon capture, utilisation and storage

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About AFID

The mission of the Alliance for Industry Decarbonization (AFID) is to foster action for decarbonisation of industrial value chains, and to promote understanding of renewables-based solutions and their adoption by industry with a view to contributing to country-specific net-zero goals. Joining AFID as a member or ecosystem knowledge partner is open to any legal entity engaged in decarbonising industry with renewable energy solutions. This includes, but is not limited to, public and private sector industrial firms, industry associations, the financial community and intergovernmental organisations.

The International Renewable Energy Agency (IRENA) co-ordinates and facilitates the activities of AFID.

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About this report

This paper was developed jointly by members of the AFID Working Group BECCUS. It builds on exchanges and discussions among the working group members that took place during a series of meetings to realise joint initiatives. This paper is informed by the experience of AFID members and ecosystem knowledge partners from different regions across the world.

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This report is available for download at: **www.allianceforindustrydecarbonization.org**

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Abbreviations

BECCUS	bioenergy with CCUS
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
DAC	direct air capture
DACS	direct air capture with storage
EJ	exajoule
ETS	emissions trading system
EUA	European Union Allowance
GCCSI	Global CCS Institute
Gt	gigatonne
$GtCO_2$	gigatonnes of CO_2
GTPA	billion tonnes per year
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
Mt	million tonnes
$MtCO_2$/yr	million tonnes of CO_2 per year
$MtCO_2$/day	million tonnes of CO_2 per day
PES	Planned Energy Scenario (IRENA)
SDG	Sustainable Development Goal
TFEC	total final energy consumption
WtE	waste-to-energy

01 Executive summary

CCUS will play an important role in the energy transition and decarbonisation

In recent years, carbon capture, utilisation and storage (CCUS) has been identified as a critical decarbonisation lever in the intricate puzzle of clean energy solutions. This includes technology-based carbon dioxide removal (CDR), such as bioenergy with CCUS (BECCUS) and direct air capture with storage (DACS). Limiting global warming to 1.5 degrees Celsius (°C) requires cutting carbon dioxide (CO_2) between 2023 and 2050 through a reduction in annual emissions of around 34 gigatonnes (Gt) from 2022 levels and cumulative carbon removals of around 500 Gt (IRENA, 2023). CCUS plays a role in scenarios from the world's most recognised international organisations, such as the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC). Based on IRENA's 1.5°C Scenario, CCUS (including BECCUS and DACS) is estimated to contribute 109 Gt of cumulative CO_2 removals by 2050.

The role of CCUS in the energy transition is largely focused on the decarbonisation of both the industrial and power sectors. This is particularly true for hard-to-abate industries such as cement, steel, chemicals, glass and paper.

CDR will play an important role in the form of negative emission contributions, which are considered essential to achieve net-zero targets and limit overall warming. This will act to offset residual CO_2 emissions that would be impossible to avoid using other decarbonisation solutions.

Strong progress is being made on the development of new commercial CCUS/BECCUS projects

As reported by the Global CCS Institute (2023), there are currently 41 industrial CCUS projects in operation worldwide. This is accompanied by a near-exponential growth in new CCUS projects (351 initiatives at various stages of development). Combining both projects in operation and in development, the total number of CCUS projects in 2023 has risen to 392, compared to 194 in 2022. These new projects will provide annual storage potential of over 361 million tonnes of CO_2 ($MtCO_2$/yr), including the development of a significant number of storage hubs. The advantage of the hub approach (both technological and economic) is that they leverage economies of scale.

New developments also include carbon capture and utilisation (CCU), which allows the transformation of CO_2 taken from emission point sources or the atmosphere into valuable low- to zero-emissions commodities, helping to promote a circular economy and reducing dependence on fossil fuels.

Case studies are provided in this this report demonstrating the potential of CCUS. The CCUS hub concept is highlighted through Eni's Hynet project in the United Kingdom, while Gulf Cryo's initiatives provide examples of applications in the field of CCU.

BECCUS provides a source of negative CO_2 emissions

Capturing and using or storing CO_2 from industrial emissions that are biogenic in origin (BECCUS) is equivalent to traditional CCUS, except has the added benefit of generating negative emissions. Assuming the availability of a sustainable bioenergy feedstock, a facility running on fossil energy with CCUS can be upgraded in the future to a BECCUS facility, using the same technology. This can be achieved simply by switching the fuel source (*e.g.* natural gas to biomethane or coal to biomass). This stepwise approach also allows hard-to-abate industries to reduce their emissions and potentially achieve negative emissions.

The largest BECCUS facility currently operating is the Illinois Industrial CCS Project that captures up to 1 $MtCO_2$/yr. It has been in operation since 2018. The development of new BECCUS projects is starting to spread, with its application at power plants that use biomass.

With the forecast increase in bioenergy usage and the progressive deployment of CCUS as an industrial decarbonisation solution, the prospects for BECCUS are expected to become increasingly promising in the coming years. Examples of plants expected to deploy BECCUS technology include Drax in the United

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Kingdom, CopenHill in Denmark, and Stockholm Exergi in Sweden. One project of significant importance is the Summit Carbon Solution project, which is being developed in the United States. It is intended to be one of the largest BECCUS projects in terms of carbon stored, with a projected capacity over 16 $MtCO_2$/yr (Summit Carbon Solutions, 2024).

Costs of BECCUS implementation

The costs of implementing BECCUS are influenced by the scale of the project and the integration with CCS technologies. According to IRENA (2023), the overall costs are higher compared to traditional CCUS due to the additional requirements for sustainable biomass. Furthermore, the Global CCS Institute (2023) emphasises that while BECCUS projects are capital-intensive, they benefit from potential cost reductions through economies of scale and supportive policies, making them increasingly feasible as part of decarbonisation strategies.

Policy and regulation are critical to facilitate the development of future CCUS and BECCUS projects

The impact of recent policy developments, particularly in Europe and North America, is driving the increase in CCUS projects being planned, as well as those progressing to construction. This growth in new projects has also largely been facilitated by investment from the private sector. Nevertheless, many challenges still need to be tackled to allow the deployment of CCUS at the required scale. These include regulatory, economic, social and environmental aspects.

A range of policy and regulatory approaches are available to incentivise CCUS as a contributor to decarbonisation. A prime example is the European Union's Emission Trading System (ETS). This is a market-based emissions permit mechanism for large industrial emitters, launched in 2005. The ETS provides a technology-agnostic incentive to reduce emissions by imposing on emitters additional costs associated with greenhouse gas emissions.

An alternative approach has been implemented in the United States in the form of a tax incentive programme known as the Section 45Q federal tax credit. It acts as a performance-based tax credit that incentivises carbon capture and sequestration or utilisation. In 2022, under the Inflation Reduction Act, the 45Q credit was increased for CCUS, along with the inclusion of DACCS.

The focus of this report is the role that CCUS and BECCUS will need to play in meeting the world's decarbonisation commitments, their current status globally, their costs, and their prospects, accompanied by CCUS case study examples. The report provides a brief overview of policy and regulation, as a more in-depth review of this subject is the primary focus of another report currently under development by the AFID Working Group on BECCUS.

02 Introduction

> *"Over the last 20 years, the role of carbon capture and storage [as a climate solution] has evolved from "nice to have" to necessary"*
>
> **Dr Sally Benson**, Deputy Director for Energy and Chief Strategist for the Energy Transition at the White House, Office of Science and Technology Policy (OSTP)

Carbon capture, utilisation and storage (CCUS) and bioenergy with CCUS (BECCUS) technologies are expected to play a critical role in the sustainable transformation of the global economy. In synergy with other decarbonisation levers, such as renewables, energy efficiency and fuel switching, CCUS and BECCUS will be strategic in achieving carbon neutrality in the next few decades, a condition deemed necessary to limit global warming to 1.5°C above pre-industrial levels (IRENA, 2023). CCUS and BECCUS are needed to contribute to reducing the industrial and energy sectors' greenhouse emissions and will be especially important for hard-to-abate industries such as cement, steel and chemicals.

The basic principles of the CCUS process are relatively straightforward and consist of three general steps. The first step is capture, where carbon dioxide (CO_2) is separated from the other flue gas components using well-known technologies, applied for decades in many industrial sectors. After the CO_2 separation, it can be transported by various means, including multi-modal solutions. These include pipelines, ships for maritime transport, and trains and tanker trucks for land transport. Once CO_2 reaches its destination, there are two alternative routes which can also work together in a synergistic way: CO_2 storage and/or utilisation.

In the case of carbon capture and storage (CCS), CO_2 is stored in deep underground geological formations, such as depleted gas fields and saline aquifers, which have been identified and shown to be suitable to contain it permanently through a rigorous process which includes several advanced sub-surface studies.

In the case of carbon capture and utilisation (CCU), CO_2 is reused in new production cycles according to the principles of the circular economy. There are multiple possible applications, including: direct use of CO_2 (as a technical gas, in the food industry or in horticulture), and the production of various chemicals, synthetic fuels, and materials for the construction sector. Utilisation technologies provide varying environmental benefits, where CO_2 emissions are only delayed in some cases (*e.g.* direct use) or permanently avoided in others (*e.g.* mineralisation).

In addition to CCUS's direct and immediate role in avoiding the emission of CO_2 from industrial sources into the atmosphere, capture and storage processes are also a necessary method of reducing CO_2 concentrations already in the atmosphere through engineered carbon dioxide removal (CDR) technologies. According to the 6th assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2022) CDR technologies will be essential to limit global warming to 1.5°C in the period to 2100.

CDR applications are divided into natural and technological solutions. The most significant technological solutions are BECCUS and direct air capture with storage (DACS). Both are based on the same principles and make use of similar technologies to CCUS, the only difference being the origin of the CO_2.

BECCUS is based on the use of sustainably grown biomass to replace fossil fuels such as coal or natural gas as an energy source for industrial processes or power generation, and then applying CCS to capture and store the resulting CO_2 emissions. Since the carbon content of the biomass was originally subtracted from the atmosphere by the natural process of photosynthesis, the entire operation can result in a net transfer of atmospheric CO_2 to the geosphere, so-called "negative emissions". The same applies with DACS, where CO_2 is captured directly from the atmosphere.

Negative emissions are considered essential to achieve net zero by offsetting residual CO_2 emissions that will not be possible to avoid through other decarbonisation solutions. But these technologies come with their own challenges to overcome (IRENA, 2023). BECCUS needs a continuous supply of sustainable biomass, and while there are many opportunities for the exploitation of agricultural waste and marginal lands, application at scale needs to avoid any risk of competing with food production. Meanwhile, DACS technology struggles with the high energy cost of sequestering CO_2 from air, where its concentration is extremely low (approximately 420 parts per million [ppm]). Both technologies would also benefit from the wider deployment of CCUS projects, which can provide local storage opportunities.

A solution for industrial decarbonisation: Deployment of CCUS at scale

CCUS processes are based on mature technologies that have been in use for many years. Gas separation technologies were developed in the first half of the 20th century, mainly to remove the acid components (CO_2 and hydrogen sulphide) from natural gas. Carbon dioxide is commonly transported by pipeline, ship and truck for several common uses in industry (*e.g.* fertilisers, technical gases, food and beverage). Underground storage is generally safe both by successful CCS projects (*e.g.* Sleipner in operation since 1996) and by the natural gas storage industry, which has been operating since the early 20th century and shares most of its technology and know-how with CO_2 storage. Nevertheless, incidents like Aliso Canyon provide important lessons for improving safety.

Recently, for reasons related to public and private environmental targets that will be further explored in the following chapters, the large majority of announced CCUS projects are dedicated to the decarbonisation of industrial emissions and their permanent geological storage (GCCSI, 2023). This new focus led to an innovative CCUS concept, which is generating considerable interest: the CCUS hub.

CCUS hubs aim to collect CO_2 from a number of different emitters and convey it to one (or more) dedicated storage locations. This approach allows the transport and storage infrastructure to be shared among all the interested emitters, thus achieving an economy of scale that allows for decreased costs and broadens access to this decarbonisation solution to medium-sized emitters. In addition, by decoupling the capture activity from the transport and storage activity, industrial players are relieved of needing the know-how and technical competence for very specialised domains, such as geology, drilling and underground monitoring, which will be provided by the operator managing the storage site. This represents a break with the past, where the CCUS business model was vertically integrated.

Europe has numerous examples of this new approach, with projects under development including those in the United Kingdom (Hynet NW, Bacton, East Coast Cluster, Viking and Acorn), Italy (Ravenna CCS), Norway (Northern Lights), the Netherlands (Porthos, L-10 and Aramis), Greece (Prinos), and Denmark (Greensand). CCUS hubs are also attracting interest in the United States and Canada. For example, the Houston Ship Channel CCS Innovation Zone project aims to build a hub with a capacity of 50 $MtCO_2$ by 2030.

CCUS hubs are a fundamental element that makes it possible to apply this crucial process for achieving carbon neutrality in new industrial contexts. This is why – from the traditional fields of fertilisers and chemicals – attention has now shifted to the cement industry (*e.g.* Norcem Brevik – Norway, K6 – France), the steel industry (*e.g.* Al Reyadah – United Arab Emirates), electricity generation (*e.g.* Boundary Dam – Canada, Drax – United Kingdom, Tundra – United States), waste-to-energy (*e.g.* BECCS Stockholm – Sweden, Fortum Oslo – Norway) and hydrogen production (*e.g.* Porthos – Netherlands, Hynet – United Kingdom).

As stated before, many of these projects would not have been large enough to economically justify a dedicated transport and storage facility, nor do the companies operating them necessarily have the skills required to build such infrastructure. The hub structure allows these industrial producers to meet their need to reduce their greenhouse gas emissions with the offer of CO_2 transport and storage services from dedicated operators who are unrelated to the activities generating the emissions.

03 The role of CCUS in the energy transition

> *"We cannot meet … the global 1.5°C target agreed to in Paris, without economy-wide deployment of carbon capture and carbon removal at scale."*
>
> US Secretary of Energy, **Jennifer M. Granholm**

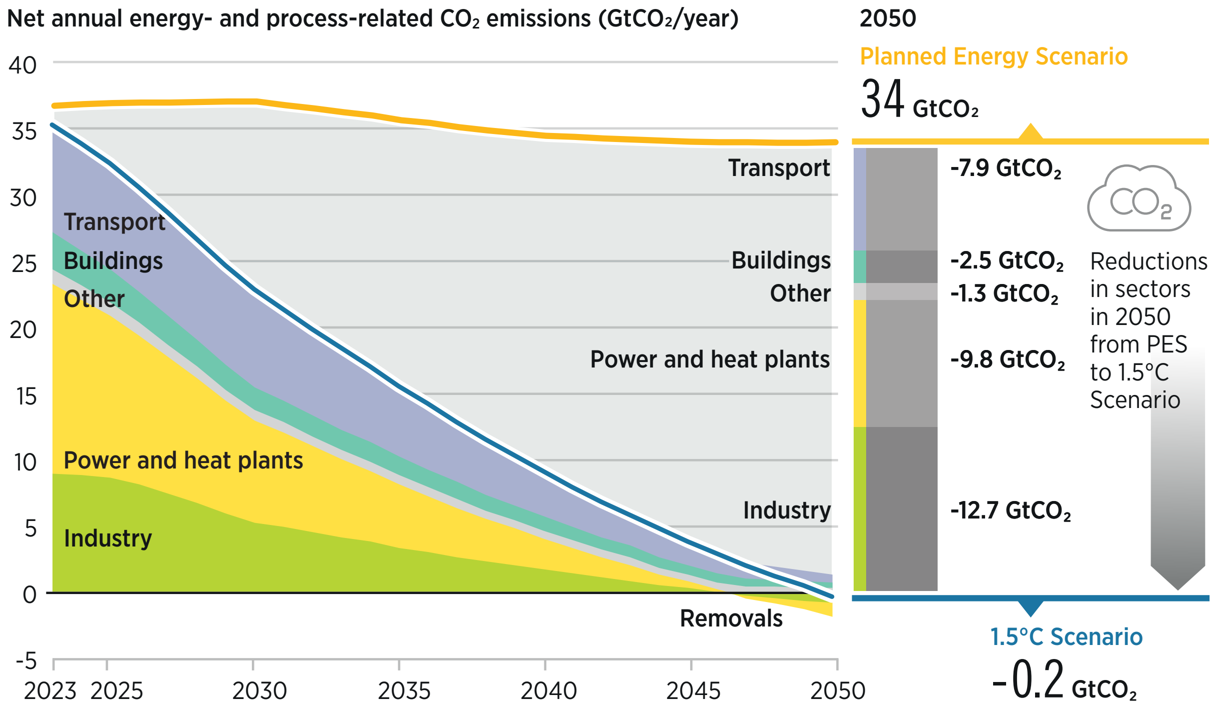
The forecast evolution of global emissions up to 2050 is shown in Figure 1 for two IRENA scenarios (IRENA, 2023).

The **Planned Energy Scenario** is grounded in the energy plans, targets, and policies established by governments, with a particular emphasis on G20 countries. It is observed that the policies adopted by governments following the Paris Agreement will at best be able to avoid a *further* increase in emissions in the coming years, but are not enough to keep the 1.5°C target within reach.

The **1.5°C Scenario** limits the global average temperature increase by the end of the 21st century to 1.5°C, relative to pre-industrial levels.

The 1.5°C Scenario will require net-zero emissions to be achieved by around 2050, using a wide array of available decarbonisation levers, with the priority on readily available technology solutions scaled up to meet the goal. Energy efficiency, renewable sources and end-use electrification will play a fundamental role, making it possible to avoid almost 70% of greenhouse gases in the next 30 years. However, these measures alone will not be sufficient. Hence, there is the need for the contribution of low-carbon energy sources, including sustainable bioenergy and biofuels, and low-emissions hydrogen and its derivatives. Finally, carbon capture, utilisation and storage (CCUS) will play a decisive role in reducing residual emissions, with bioenergy with CCUS (BECCUS) and other carbon dioxide removal (CDR) technologies ensuring negative emissions. Overall, these technologies will account for over 19% of the annual CO_2 emissions abatement in 2050 (Figure 2 Carbon dioxide emissions abatement under the 1.5°C Scenario in 2050), with a cumulative total of 109 gigatonnes of CO_2 ($GtCO_2$) removed over the period 2023-2050.

FIGURE 1 Evolution of global emissions and temperature rise according to the Planned Energy Scenario and 1.5°C Scenario

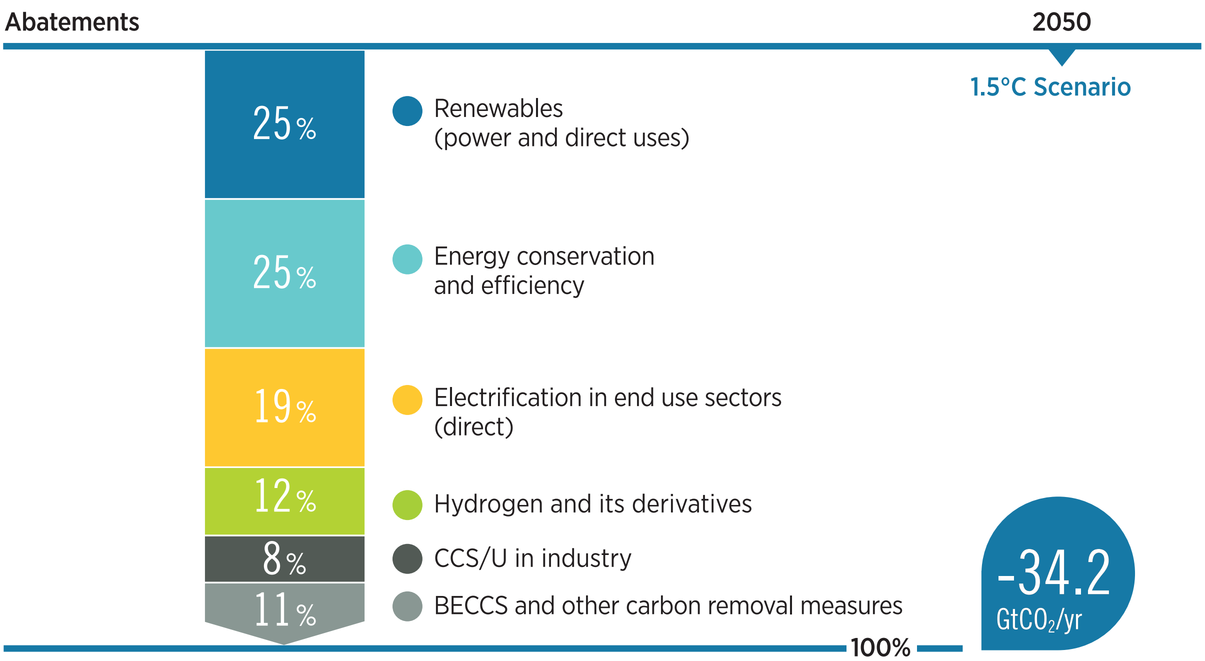


Source: (IRENA, 2023).

Note: PES = planned energy scenario; $GtCO_2$/yr = gigatonnes of CO_2 per year.

The 6th IPCC Assessment Report explicitly declares that CCUS and CDR technologies will be essential to achieve carbon neutrality by the middle of the century (and therefore constrain the global temperature increase to less than 1.5°C). This view is shared by all major international organisations. There is a general consensus on the need for CCUS, albeit to varying degrees.

FIGURE 2 Carbon dioxide emissions abatement under the 1.5°C Scenario in 2050

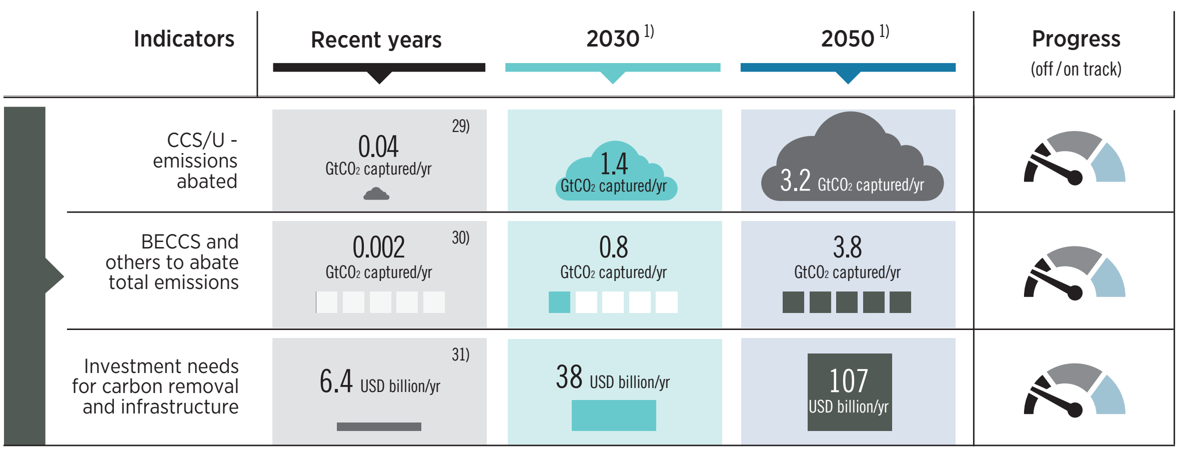


Source: (IRENA, 2023).

Notes: BECCS = bioenergy with carbon capture and storage; CCS/U = carbon capture and storage or utilisation; $GtCO_2$/yr = gigatonnes of CO_2 per year.

As shown in Figure 3, IRENA (2023) has BECCUS and other removals at over 54% of the total 7 $GtCO_2$/year captured in 2050. Of this total, 84% is from the power and heat sectors and 16% is from industry.

FIGURE 3 CCUS and BECCUS contribution to achieving the 1.5°C Scenario

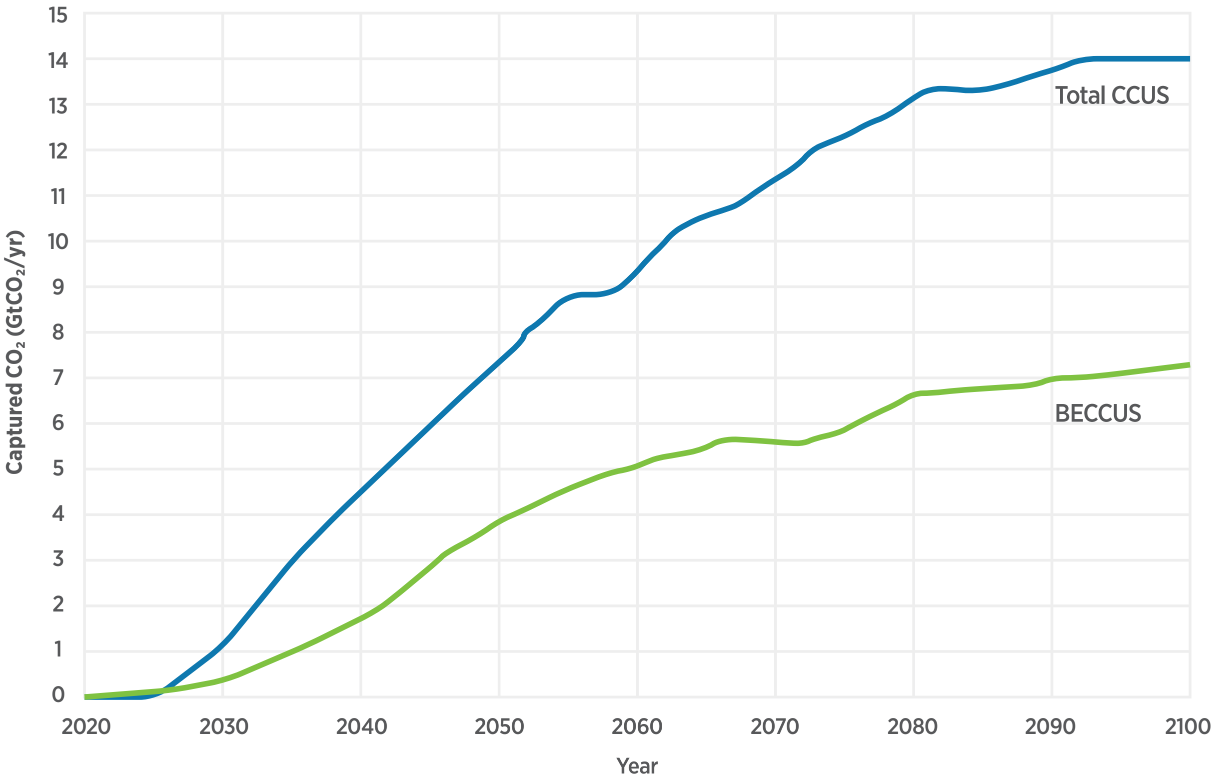


Source: (IRENA, 2023).

Notes: BECCS = bioenergy with carbon capture and storage; CCS/U = carbon capture and storage or utilisation; $GtCO_2$/yr = gigatonnes of CO_2 per year.

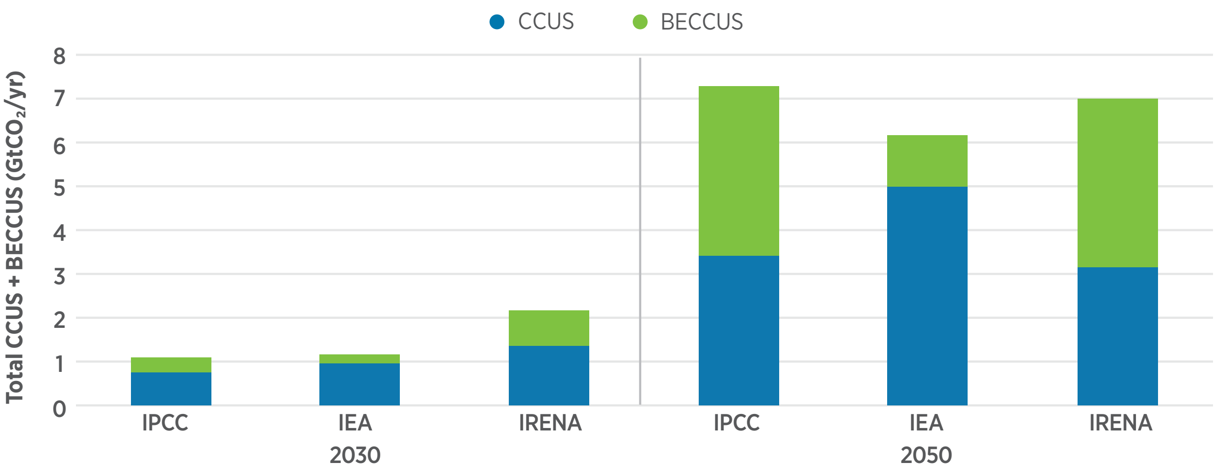
Figure 4 shows CO_2 capture amounts comparing the median values from the IPCC (2022) C1 case (97 scenarios, < 1.5°C with no overshoot). In Figure 5 these results are compared to the International Energy Agency (IEA) Net Zero Emissions Scenario (IEA, 2023b) and the IRENA 1.5°C Scenario (2023). In all these scenarios CCUS is a key decarbonisation lever in limiting global warming to 1.5°C. There is general agreement among the three organisations on the total CCUS required in 2050 (varying in the range 6.04-7.2 $GtCO_2$/yr). BECCUS is also present in all three, with both the IPCC and IRENA approaching around 4 $GtCO_2$/yr, representing over half of the total CCUS conducted in 2050, while the IEA Net Zero Scenario is less reliant on BECCUS at around 1.2 $GtCO_2$/yr.

FIGURE 4 Median values for the total use of CCUS (blue) and BECCUS (green) technologies from 2020-2100, IPCC C1 Scenarios



Source: (IIASA, 2022).

FIGURE 5 Comparison of total use of CCUS and BECCUS in IPCC, C1 Scenarios, IEA Net Zero Scenario and IRENA 1.5°C Scenario



Based on: (IEA, 2023b; IIASA, 2022; IRENA, 2023).

CCUS in industry

The importance of CCUS in the energy transition is mainly related to its role in decarbonising industry. This is particularly true for the hard-to-abate industrial sectors, where CCUS is a critical mitigation option. The deployment of CCUS to avoid part of the CO_2 emissions in the hard-to-abate sectors and CCUS with CDR (more specifically, BECCUS) to offset residual emissions is inevitable if net-zero CO_2 or greenhouse gas emissions are to be reached (IPCC, 2022). For these activities, emissions are predominantly linked to the chemical-physical transformations that are inherent to the process itself. Currently, CCUS is one of the few technologies able to significantly reduce these emissions and the only solution is to intercept them before they reach the atmosphere. Examples include the production of cement, where about two-thirds of the CO_2 comes from the calcination of limestone, and the steel industry, in which carbon is an essential element in primary steel metallurgy. In these cases, energy efficiency and renewable sources have limited effectiveness. IRENA (2023) estimates that CCUS will contribute to the reduction of 2.1 $MtCO_2$/yr in the cement industry and 0.3 $MtCO_2$/yr in the steel industry in 2050.

CCUS in electricity generation

In the electricity sector, the replacement of fossil fuels with renewables represents the cornerstone of the energy transition. As part of the European Green Deal and the REPowerEU plan, the European Union provisionally agreed in 2023 to accelerate the deployment of renewables and raised the binding 2030 target for 42.5% of final energy consumption to be from renewable sources to an ambition to reach 45% (European Commission, 2023). According to the IRENA 1.5°C Scenario (2023), the worldwide share of renewables in electric generation will increase to 35% in 2030 and all the way to 82% by 2050.

A strong increase in electricity demand is predicted in the coming decades owing to the transition to renewable sources in the power sector and the electrification of final consumption to achieve the gradual replacement of fossil sources in various sectors. This is happening in the case of electric vehicles for light vehicle transport and heat pumps for both domestic heating and industrial applications and is expected to occur in renewable hydrogen production. For example, electricity's share of final energy consumption is expected to increase from 22% to 51% by 2050 (IRENA, 2023) in the 1.5°C Scenario.

The combination of both the transition of the electricity generation sector to high shares of renewables and the vigorous increase in electricity demand will require a deep transformation of national and international electricity grids to ensure energy security and stable power delivery.

A fundamental aspect to consider is the balancing of electricity distribution networks, which essentially translates into the need to match power supply and demand. The variable (both daily and seasonal) and non-programmable (non-dispatchable) nature of renewable energy sources represents a challenge in this regard. The higher the percentage of renewable sources in the energy mix, the higher the need in the future to have secondary systems that guarantee the balancing of electricity grids. Possible solutions vary from electric accumulators (batteries), production of renewable hydrogen as an energy storage system, pumped-storage hydro and the use of thermoelectric plants equipped with CCUS to make up for periods of unavailability of renewable energy, whilst still meeting the need to minimise greenhouse gas emissions. This is not an exhaustive list, and all options will have their ownbenefits and drawbacks based on the particular situation.

Each solution can help balance the network and features some specific advantages and limitations. For example, battery storage allows for electricity on demand, but the needed electric accumulator capacity is challenging to optimise due to seasonal variations. Hydrogen can be combined with excess renewable power to provide a convenient long-term energy vector, but its low volumetric energy density requires large storage facilities. Thermo-electric plants powered by traditional sources can provide on-demand flexibility but require an investment in CCUS facilities to limit associated greenhouse gas emissions. Hence, a multi-pronged approach could combine different solutions, taking advantage of synergies, rather than being limited to a single solution.

For BECCUS, its role in decarbonising the power sector is linked to the share of thermo-electric plants that will have their emissions abated through carbon capture. The use of biomass as energy source could be implemented directly in a new plant or replacing the fossil feedstock of an existing plant, possibly taking advantage of a capture facility already in operation. BECCUS has the added benefit of offsetting residual emissions through the generation of negative emissions.

CCU in industry

> *"Each atom of carbon we can recycle is an atom of fossil carbon left in the underground for next generations that will not reach the atmosphere today."*
>
> *Aresta et al. (2016)*

The circular carbon economy is an important concept in the quest to efficiently manage the world's excessive CO_2 emissions. It is a closed-loop system involving 4Rs: reduce, reuse, recycle and remove. By applying these 4Rs through carbon capture and utilisation (CCU), the amount of CO_2 emitted into the atmosphere could be substantially reduced.

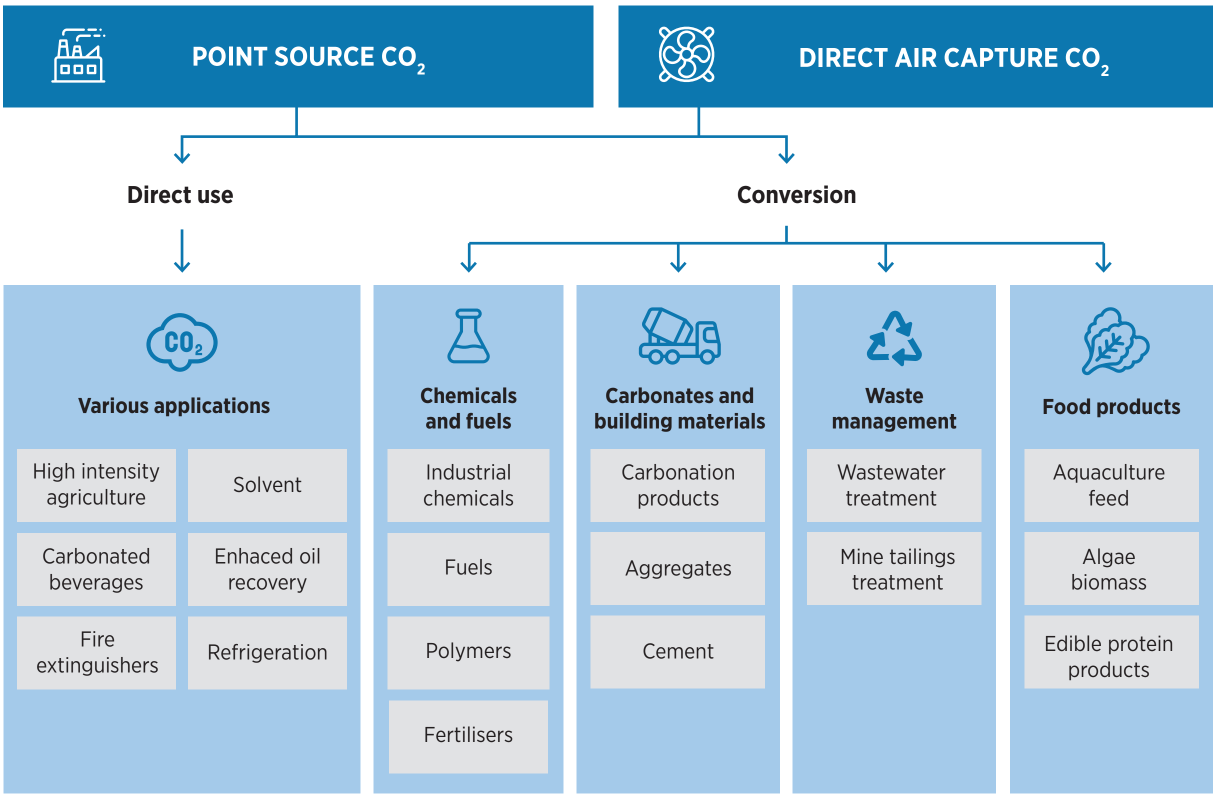
CCU is defined as the conversion of CO_2 captured from emission sources or the atmosphere into valuable lower or zero emission products. This differs from carbon capture and storage (CCS) where CO_2 is captured, transported and buried in underground geological formations for permanent storage.

CCU aligns with the principles of the circular economy, where resources are used efficiently, and waste is minimised. By converting CO_2 into useful products, CCU can help close the loop in material cycles and reduce dependence on fossil fuels. CCU is a promising component in the decarbonisation toolkit, contributing to both emissions reduction and the creation of value from captured carbon. Nevertheless, CCU is not a standalone solution, but rather complements other decarbonisation strategies. It can work in conjunction with CCS to achieve broader emission reduction goals.

It is important to highlight that while storage and utilisation are both important and strategic for achieving full carbon neutrality, they are not equivalent in terms of the volumes of emissions that can be eliminated. In fact, in its Sustainable Development Scenario, the IEA (2019) estimates that utilisation technologies would be able to absorb and eliminate 5-10% of the CO_2 captured, while the rest would go to permanent storage. However, these represent significant volumes, which could reach 400 $MtCO_2$/yr in 2035 and exceed 750 $MtCO_2$/yr in 2050.

CCU creates the opportunity to capture emitted CO_2 and convert it for use in products from a wide variety of industries. The different use cases or products compatible with CO_2 utilisation can be grouped into broad areas (see Figure 6).

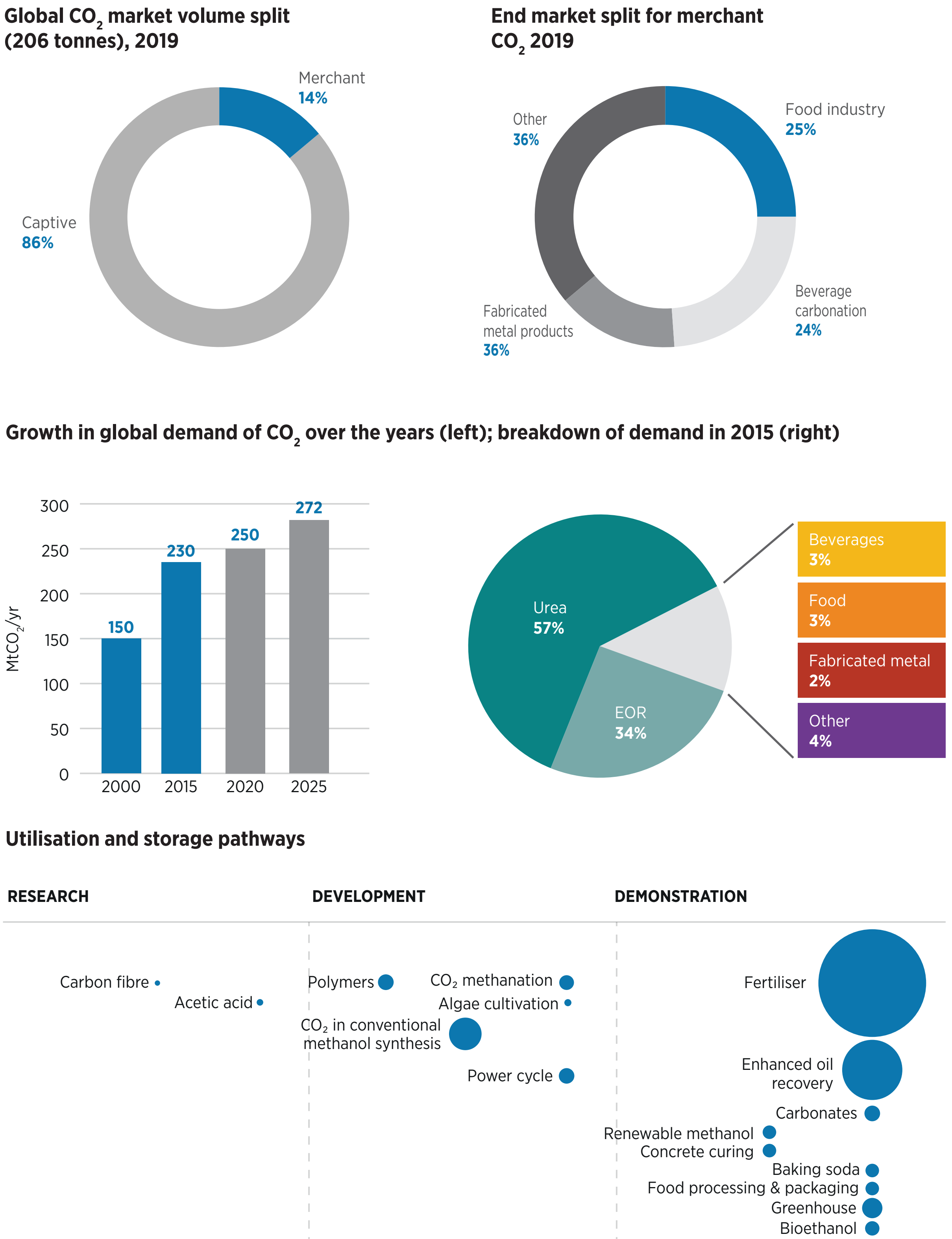
FIGURE 6 Carbon dioxide utilisation pathways



Source: (CSIRO, 2021).

As shown in Figure 7, according to estimates by the IEA (2019), the total market for the direct use of CO_2 is about 250 $MtCO_2/yr$. More than half of this total (57%) is related to the production of urea for the fertiliser industry. While providing an economic return for the valorisation of CO_2, there is no agreement on the environmental benefits of these uses, hence they will not be considered in this document. This limits the current market to approximately 23 $MtCO_2/yr$.

FIGURE 7 Carbon dioxide utilisation demand by market and application



Sources: (GCCSI, 2019; HSBC, 2021; IEA, 2019)

Notes: EOR = enhanced oil recovery; $MtCO_2/yr$ = million tonne of carbon dioxide per year.

This diversity of applications is important and can be leveraged to provide both flexibility in entering a range of green markets as CCU technologies evolve, and the opportunity to follow a diversification strategy for the decarbonisation of hard-to-abate processes and industries.

In addition, CCU can be used to offset some of the costs of CO_2 capture through revenue generated from utilisation and to add value to infrastructure investment.

It is important to mention that not all CCU applications are at the same stage of development or offer the same level of impact:

a. Market development: Some CCU applications are more mature in their market development. This means they have progressed further in along the path of research, testing and commercialisation. More mature applications are likely to have existing infrastructure and established supply chains, making it easier to implement them on a larger scale.

b. Carbon mitigation potential: Different CCU applications have varying levels of effectiveness when it comes to reducing carbon emissions. Some might have a higher carbon mitigation potential, meaning they can capture and utilise larger amounts of CO_2 from the atmosphere or industrial processes. These applications are particularly valuable for achieving a significant reduction in overall carbon emissions.

c. Total market potential: CCU applications also differ in their total market potential. Some might have a wider range of potential applications across various industries, which could lead to a larger overall market. This could be due to their adaptability, versatility or compatibility with existing processes.

Decision makers, investors and researchers are advised to consider these factors when prioritising and investing resources in CCU applications and technologies. Depending on the context and goals, some applications might be more suitable for immediate deployment due to their advanced market readiness, while others might require further development before they can be effectively scaled up.

Ultimately, a balanced approach that considers both the carbon mitigation potential and the total market potential of different CCU applications can lead to a more effective strategy for addressing climate change and transitioning to a more sustainable future.

The various ways of utilising CO_2 can be split into two main streams:

- Direct reuse: the recovered CO_2 is reused with no conversion.
- Recycling or conversion: the recovered CO_2 is either biologically, minerally or chemically transformed into new components

Direct reuse

Direct reuse mainly consists of applying CO_2 directly with no conversion for:

- Food applications such as the carbonation of soft drinks, food cryo-freezing or dry ice for cold transport.
- Many other traditional industrial applications such as arc welding, firefighting and dry ice blast cleaning.

Established CO_2 demand from these conventional markets could be leveraged as initial off-takers for the development of new capture plants in the short to medium term.

However, these industries only offer a very short CO_2 retention time before it is released back into the atmosphere. While these applications might not offer long-term storage benefits, they can still contribute to reducing emissions (Ontario, 2022) by displacing the use of fossil fuels or other high-carbon inputs.

CO_2 conversion

Biological conversion

Two main biological applications should be mentioned:

- **CO_2 enrichment in greenhouses to boost crop production.** The CO_2 is converted by plants into sugar and stored as biomass. The biological conversion of CO_2 presents an opportunity to capitalise on growing global food export markets. For example, in the Middle East countries of Gulf Cooperation Council, face unique challenges due to high reliance on food imports and the need for enhanced food security. The COVID-19 pandemic has highlighted vulnerabilities in global supply chains, further emphasising the importance of locally produced food. Implementing advanced agricultural practices, such as CO_2 enrichment, can play a crucial role in increasing domestic food production and reducing dependence on imports, in addition to achieving sustainability goals (Ontario, 2022).
- **Algae production.** Algae, including microalgae, are highly efficient at absorbing CO_2 and converting it into biomass through photosynthesis, with the ability to actively absorb CO_2 from exhaust gases during this process (Iglina *et al.*, 2022). Microalgae have the ability to capture significantly more CO_2 per unit of biomass, biofixing carbon dioxide up to 50 times more efficiently than many other plant species (Bhola *et al.*, 2014). This makes them a valuable tool for carbon sequestration and mitigating greenhouse gas emissions. Algae have a wide range of applications across various industries:
  - Food and animal feed: certain types of algae are rich in nutrients and can be used as a source of food and feed for both humans and animals. Algae-based protein and omega-3 fatty acids are examples of valuable nutritional components (Kusmayadi *et al.*, 2021).
  - Biofuels: algae can be processed to extract oils that can be converted into biofuels, such as biodiesel. This could contribute to cleaner energy sources and reduce reliance on fossil fuels (Jassinnee *et al.*, 2016).
  - Plastics and carbon fibre: algae-based materials can be used to produce bioplastics and even carbon fibre, offering more sustainable alternatives to traditional materials (Cheah *et al.*, 2023; Mathijsen, 2019).

Mineral conversion

The mineral conversion of CO_2 into solid or carbonate-based products can drive near-term opportunities to utilise waste from heavy industry and mining, lock CO_2 away permanently and lower the carbon intensity of the end products.

Carbonate products from CCU can be cost-competitive and have a wide range of uses, including as building materials such as insulation and bricks, use in chemicals and in food and nutrition (Australia's National Science Agency, 2021).

Concrete is the most used man-made material on the planet and demand for concrete is projected to grow. However, the cement industry is already responsible for more than 8% of global CO_2 emissions and cement is a carbon-intensive product. Each cubic metre of concrete produced emits approximately half a tonne of CO_2 (Energypost.eu, 2023).

The UN Sustainable Development Goals (SDGs) emphasise the need to reduce carbon emissions, particularly in industries like construction, with the ambition of reducing carbon emissions from building materials.

World Green Building Council has issued a new vision in 2020 including that (World Green Building Council, 2020):

- by 2030, all new buildings, infrastructure and renovations will have at least 40% less embodied carbon with significant upfront carbon reduction, and all new buildings are net-zero operational carbon.
- by 2050, new buildings, infrastructure and renovations will have net-zero embodied carbon, and all buildings, including existing buildings must be net-zero operational carbon.

For concrete, the mineral conversion solution presents an immediate opportunity. It consists of the precise injection of CO_2 in the ready-mix. Once injected, the CO_2 reacts with calcium ions in the cement to form a nano-sized mineral, calcium carbonate, which is locked away forever in the concrete. By doing so, the volume of cement and aggregates required can be reduced, thus reducing the carbon intensity and feedstock costs. By using this technology the construction sector can enhance the environmental profile of the products it uses and meet evolving sustainability standards.

Chemical conversion

Three main chemical applications should be mentioned:

- **Desalination:** using captured CO_2 for chemical conversion in the desalination sector is a noteworthy strategy to address the carbon emissions associated with this critical industry.

Desalination is vital in regions with limited freshwater resources. In the Middle East, where well over half of the world's desalination capacity is located, two-thirds of the water produced is from fossil fuel-based thermal desalination processes, which emit significant amounts of CO_2.

For each 1 000 m^3 of desalinated water produced, around 7 tonnes of CO_2 are emitted. CCU presents an immediate-term solution for decarbonising the desalination sector by replacing the use of fossil-fuel generated CO_2 with the captured CO_2 waste for the water remineralisation process.

Desalinated water lacks essential minerals, making it less palatable and potentially harmful for consumption. Remineralisation is crucial to restore the water's quality and safety. The chemical conversion of CO_2 into carbonic acid, which then reacts with limestone, can achieve effective remineralisation.

The estimated CO_2 requirement for water remineralisation, such as 35 kg of recovered CO_2 per 1 000 m^3 of desalinated water produced, provides a clear understanding of the potential scale of CO_2 utilisation needed for this process.

According to Gulf Cryo, by 2025 the GCC states will require around 250 000 tonnes of CO_2 per annum for their desalination plants.

By integrating CCU into the desalination sector for water remineralisation, countries can simultaneously tackle the challenges of water quality and carbon emissions. This pragmatic approach highlights the interconnectedness of various sustainability goals and the potential for innovative solutions to address complex challenges. As regions strive to balance water security with environmental concerns, such strategies offer a path towards a more sustainable future.

- **Synthetic fuels:** the captured CO_2 can be recycled into a feedstock combined with green hydrogen (produced using renewable energy sources) in a synthetic fuel process.

Synthetic fuels are also known as e-fuels or electrofuels. They can be used in existing combustion engines without significant modification. Carbon is locked away until the synthetic fuel is combusted, at which point it is re-released into the atmosphere, but the process remains carbon-neutral when the CO_2 is captured and reused in the cycle.

Carbon-neutral liquid fuels are likely the most significant potential market for captured CO_2. The demand for liquid fuels is substantial and is likely to persist even as electrification advances. The major potential market for synthetic fuels is the principal difficult-to-decarbonise sectors – industry, heavy-duty transport and aviation.

Synthetic fuels provide an opportunity to address emissions in these sectors by offering a renewable alternative without the need for extensive infrastructure changes.

While the concept of synthetic fuels is promising, there are still technological and economic challenges to overcome. Research and development efforts are ongoing to improve the efficiency and cost-effectiveness of the production processes.

Chemicals and plastics: currently, only a handful of chemical applications of CO_2 are commercialised at scale. CO_2-derived chemicals and plastics remain quite expensive. As with synthetic fuels, the emerging hydrogen industry supports the long-term transition to lower-emission chemicals, but it may require strategic investment to move at a faster pace.

CO_2 can be transformed into valuable chemical intermediates, such as methanol and syngas. These intermediates can serve as feedstocks for various industries, including petrochemicals and pharmaceuticals. Utilising captured CO_2 as a feedstock contributes to reducing reliance on fossil fuels for these chemicals.

Transforming CO_2 into polymers that act as precursors for plastics, adhesives and pharmaceuticals has significant potential. Creating a circular economy by incorporating captured CO_2 into polymer production reduces the environmental impact of plastics while also providing a valuable market for captured CO_2.

Transitioning industries from traditional chemical processes to CO_2-based alternatives might take time due to infrastructure, technology and cost considerations. However, the long-term environmental gains could be substantial.

Re-emission of utilised CO_2 and its timescale

As per IRENA's 2021 report, to consider the CCU as a viable strategy for the decarbonisation of industry or CO_2 emission reductions, one major factor has to be considered: the recovered CO_2 should be utilised in products that lock in CO_2 emissions for an extended period of time (IRENA, 2021). It is challenging to trace CO_2 across multiple end uses. While CO_2 might be stored for the long term in building materials, the lock-in effects in industries like food and beverages, and fuels such as ammonia and methanol, are considered to be short term, since the CO_2 is emitted back into the atmosphere within days or weeks. Therefore, CCU benefits should be closely considered according to the CO_2 application that is being implemented (IRENA, 2021).

FIGURE 8 Timescale for the release of CO_2 and its likelihood in different applications of captured CO_2

<table>
<tr><th colspan="2"></th><th colspan="6">Timescale of release of CO₂</th></tr>
<tr><th colspan="2"></th><th>Days</th><th>Weeks</th><th>Months</th><th>Decades</th><th>Centuries</th><th>Millenia</th></tr>
<tr><th rowspan="3">Likelihood of release</th><th>Low</th><td></td><td></td><td></td><td></td><td>Building materials</td><td>CO₂-EOR</td></tr>
<tr><th rowspan="2">High</th><td rowspan="2">Urea, methanol</td><td colspan="2">CO₂ derived fuels (Fischer–Tropsch derived fuels, methane, etc)</td><td rowspan="2">Plastics</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td colspan="2">Microalgae for biofuels, biomass or bioproducts</td></tr>
</table>

Source: (IRENA, 2021).

Note: EOR = enhanced oil recovery.

CCUS in hydrogen production

Hydrogen has potential decarbonisation applications in both the industrial and long-haul transport sectors. CCUS, in addition to its decisive role in direct abatement of emissions (especially in the industrial sector), could also play a very important role in promoting the growth of the hydrogen market.

Hydrogen, which is produced from fossil fuels with CCUS or bioenergy with BECCUS could act as a bridging solution as hydrogen produced from renewable electricity scales up and becomes more economically affordable (IRENA, 2023). Currently, electrolytic hydrogen can cost between two and three times more than producing hydrogen with CCUS depending on the location. With reduced renewable electricity costs and continued improvements in electrolyser technologies, electrolytic hydrogen has the potential to be cost-competitive in around the next decade (IRENA, 2023).

In the near to medium term, CCUS and BECCUS can help contribute to the development of this new emerging hydrogen market by guaranteeing competitive costs, providing a low environmental impact, and offering significant carbon emission reductions over traditional hydrogen production.

Audio und werbung © shutterstock.com

04 The current status of CCUS/BECCUS worldwide

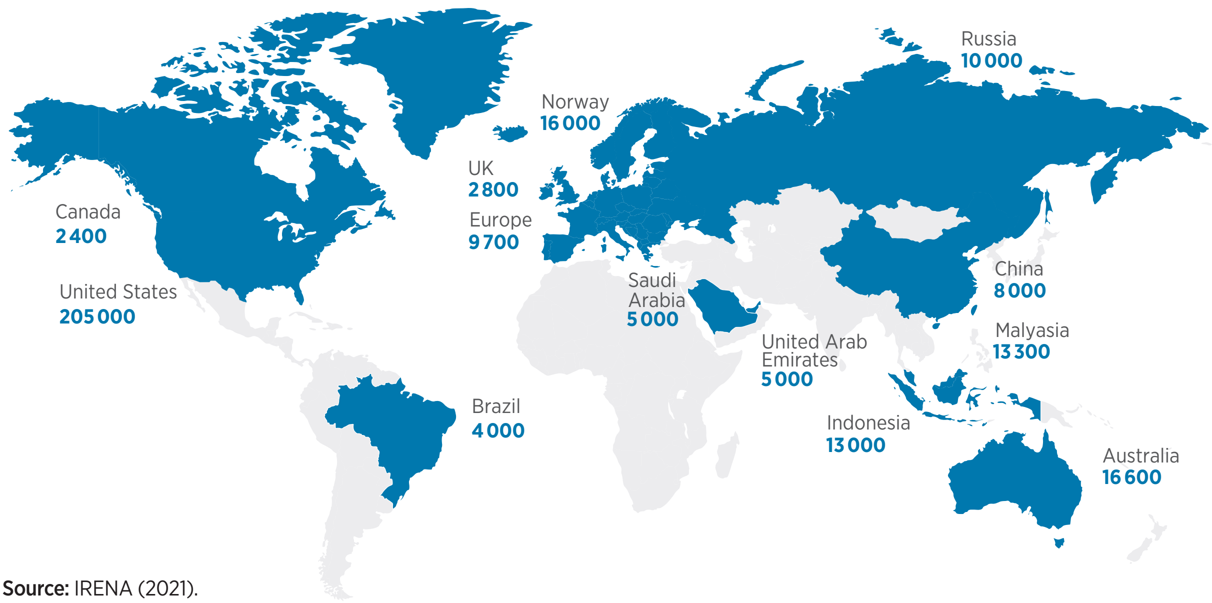
> *"We have little time left to avoid some of the worst impacts of climate change. We can tackle this challenge by avoiding carbon emissions through point source carbon capture coupled to reliable storage (CCS), and by removing carbon dioxide from the accumulated pool in the atmosphere (CDR). If done strategically and collaboratively, deploying these approaches will not only help us address the climate crisis, but will also spur the creation of high-quality clean economy jobs – helping those populations and communities that have been disproportionately affected by climate change."*
>
> **Dr Jennifer Wilcox**, Principal Deputy Assistant Secretary, Office of Fossil Energy and Carbon Management, US Department of Energy

The deployment of carbon capture, utilisation and storage (CCUS) and bioenergy with CCUS (BECCUS) technologies holds great promise for industry decarbonisation. The projections presented in the IRENA *World energy transitions outlook* report (2023) forecast a requirement for 109 GtCO_2 to be sequestered between 2023 and 2050. The best available estimates of worldwide storage capacity suggest that this will not constitute a barrier for CCUS/BECCUS implementation.

Potential long-term geological storage solutions comprise deep saline formations and depleted oil and gas fields. Estimating the capacity of saline aquifers is quite complex and as a result the ranges of capacity found in literature are very wide. In the case of depleted reservoirs, estimates are deemed more accurate as these assets are better known and monitored. In either case, these surveys are incomplete because not all countries are included (*e.g.* the whole African continent is missing from Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of AFID or IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.).

According to the IPCC (2022), the worldwide available storage capacity ranges in the thousands of gigatonnes (Gt). IEA (2023a) estimates it to be 8 000-55 000 Gt, while IRENA (2021) suggests it to be about 12 000 Gt for saline aquifers and 310 Gt at minimum for depleted reservoirs. From the GCSSI Status report (2023), the global storage capacity is over 14 000 Gt (saline aquifers and depleted reservoirs). All these estimations indicate an abundance of geological storage capacity, surpassing the needs of CCUS and BECCUS technologies by a significant margin.

FIGURE 9 Carbon dioxide storage resources (Mt) in major oil and gas fields (depleted reservoirs only)



Source: IRENA (2021).

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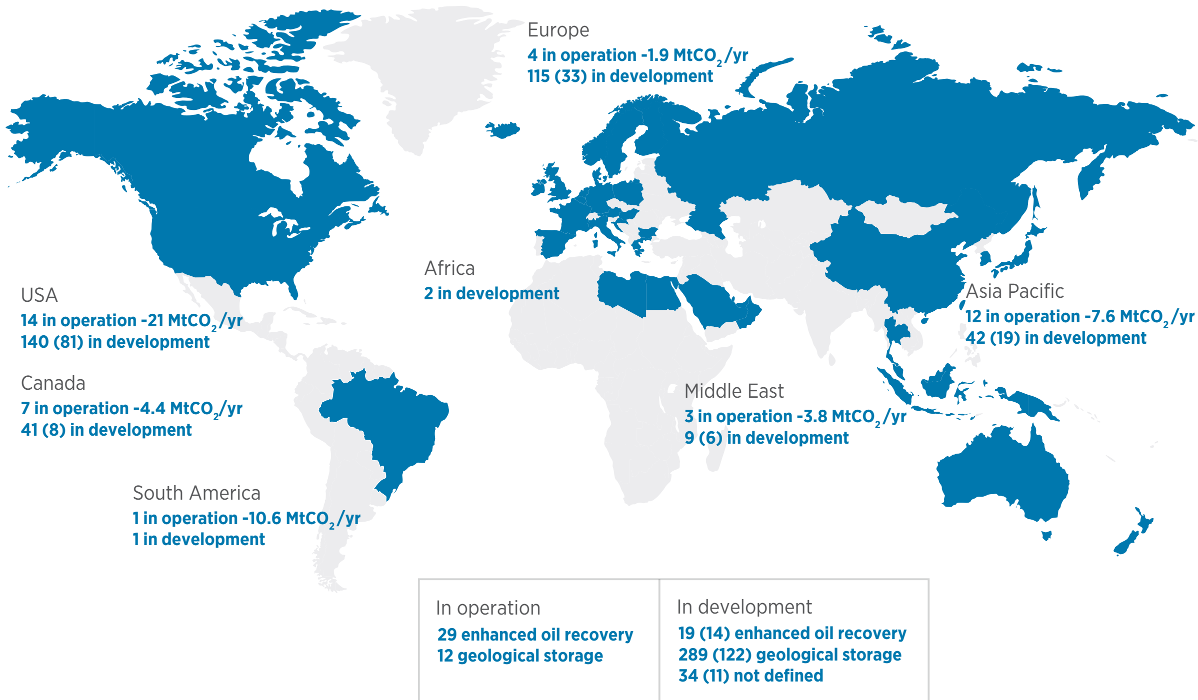
However, it is essential to highlight that challenges may arise due to the uneven distribution of the global geological storage capacity. Some regions may face difficulties in deploying CCUS technologies due to limited suitable storage sites in their vicinity. In order to effectively implement these promising climate solutions worldwide, it is crucial to ensure equitable access to storage resources and consider geographical constraints. The mapping of storage resources and streamlining permitting processes can help facilitate progress of future CCUS projects.

Status of CCUS projects

As of November 2023, according to the annual report from the GCCSI (2023), 41 industrial CCUS projects were operational on a global scale, some of them active since the 1970s. These 41 commercial projects, which operate at commercial scale and therefore should not be confused with the much more numerous research and development (R&D) centres and pilot plants, clearly demonstrate that the technological process of CCUS is mature and immediately applicable. Every year these projects avoid the emission of over 49 $MtCO_2$ into the atmosphere. Meanwhile, over 351 new projects are currently at various stages of development, with an additional storage potential of more than 361 $MtCO_2$. To further demonstrate that new CCUS projects are being developed mainly for environmental purposes, the vast majority of new projects are devoted to permanent geological storage.

FIGURE 10 Commercial projects operating and under development in the world.



Based on: GCCSI (2023).

Note: Data in blue are projects at an advanced stage of development.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of AFID or IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

One of world-first project is Sleipner in Norway (1996), which was the first project dedicated to permanent geological storage and hence exclusively for environmental purposes. Over the years, it has avoided over 20 $MtCO_2$ emissions. The two largest projects worldwide are Shute Creek (1986, United States) and the Petrobras Santos Basin Project (2008, Brazil), which together store over 17 $MtCO_2$/yr.

Europe currently has four projects in operation: Sleipner and Snohvit in Norway, Orca in Iceland and MOL Szank in Hungary. The Orca project in Iceland stores only 4 000 tonnes of CO_2 per year but is worth mentioning as it is the first commercial direct air capture (DAC) project. There are 115 projects in development in Europe, 33 of which are at an advanced stage. In this region the development of CCUS hubs is gaining momentum, with a significant number of hubs planned, particularly in Northern Europe.

North America has the highest number of projects in operation (21), with many new projects in various phases of development. A peculiar characteristic of the North American region is the high amount of capture projects related to bioethanol production, due to the significant presence of this industry in North America.

The Asia Pacific region has 12 projects in operation and 42 in development, of which 19 are at an advanced stage. In this region, the idea of CCUS hubs is also becoming popular, with the development of this kind of project mainly in China and Australia. South America has only one project, Santos Basin of Petrobras in Brazil. In the Middle East, three projects are in operation and nine are in development, of which six are at an advanced stage. Africa has two new projects in development.

Status of BECCUS projects

Today the largest operating BECCUS facility is the Illinois Industrial CCS Project, which has captured up to 1 $MtCO_2$/yr in operation since 2018. Owned by Archer Daniels Midland, this facility produces ethanol from corn at its Decatur plant, producing CO_2 as part of the fermentation process. The CO_2 is stored in a dedicated geological storage site deep underneath the facility. This has been followed by the Red Trail Energy bioethanol project, which started up in 2022.

The development of new BECCUS projects is starting to spread with the technology's application to power plants that use biomass and waste-to-energy (WtE) plants. This is the case, for example, at the Drax power plant in the United Kingdom, the Copenhill (Amager Bakke) WtE plant in Denmark, the Hafslund Oslo Celsios CCS project in Norway (currently on hold for cost review), and the Stockholm Exergi plant in Sweden. Also of importance is the Summit Carbon Solution project which is being developed in United States. This is set to be one of the largest projects in terms of carbon stored, which in March 2024 announced a future capacity over 16 $MtCO_2$/yr, which will be collected from 57 ethanol producing facilities across the Midwest, transported and then permanently stored (Summit Carbon Solutions, 2024).

Making CCUS work in the Asia-Pacific

The global distribution of CCUS projects is uneven. The governments of North America, Canada and Europe have introduced policies to support CCUS hubs, including development grants and the licensing and permitting of geological CO_2 storage. These are also supported by high carbon taxes, low carbon fuel standards and tax credits for depreciation. Across most of Asia-Pacific it is a different story. Despite a growing pipeline, only Australia and Japan have operational CCUS projects, and most governments are only now recognising that policy support is essential to drive investment.

Unlocking CCUS potential in Asia Pacific is not an easy task. The three key challenges are:

- The need for supporting regulations and incentives.
- The lack of developmental projects to support technology.
- Access to finance.

It is important for governments in this region to accelerate efforts towards:

- Supporting CCUS demonstration projects, especially in hard-to-abate sectors.
- Creating market mechanisms such as a carbon market and allowances to motivate and create confidence in external capital injection into CCUS.
- Fast tracking policies by defining CCUS in the overall decarbonisation pathway of the nation.

05 The development of the CCUS/BECCUS market

"I believe that CCUS has incredible potential in our race to reach climate neutrality. And without CCS and CCU, it will be practically impossible to limit global warming to the 1.5 degrees Celsius objective."

Kadri Simpson, EU Commissioner of Energy, European Commission

Currently, the carbon capture, utilisation and storage (CCUS) market is still at an early phase of development, despite being a mature and proven technology. The main reason for this is that the abatement of CO_2 emissions strictly for environmental purposes historically had no direct economic value in itself. Other decarbonisation levers have been prioritised in the past because they could provide side economic benefits, such as a reduced energy consumption for energy efficiency, or reduced energy-related costs for renewables in recent years. Regarding bioenergy with CCUS (BECCUS), the bioenergy part produces energy and therefore offers value added, but large-scale application has in the past been limited to the complex supply chain of sustainable biomass.

These "low-hanging fruit" dynamics are efficient and feasible, but they have limited application in the decarbonisation of industry, especially in the hard-to-abate sectors, where CCUS/BECCUS will be one of few possibilities to achieve the deep decarbonisation of manufacturing activities, and ultimately reach net-zero emissions. In regions with younger assets, capturing carbon can be a promising solution.

In recent years, a significant evolution in both the international political agenda and public opinion has been observed, resulting in a stronger push to limit greenhouse gas emissions and to promote the energy transition. Sustainability plays a fundamental role in government and public agendas, and one of the most important methods to measure the positive impact of an organisation are the Sustainable Development Goals (SDGs), as defined by the United Nations (UN). Corporate sustainability performance, measuring the impact of private companies on the SDGs, has been shown to be positively correlated to financial performance (Saha *et al.*, 2024). Alignment with these goals is necessary to strengthen public support and open new R&D funding opportunities. This also opens a new mode to compete in the market with increasing preference by the public to select environmentally sustainable products and services.

This new paradigm resulted in a major change to the business "ecosystem" for CCUS and other decarbonisation technologies. According to Adner and Kapoor (2015) the speed with which technology is applied is not only a result of the performance of the technology itself, but largely depends on the complex interdependencies in the broader ecosystem of components and complementarities in which the technologies are embedded. Public acceptance, policies, national/international and corporate environmental targets, regulatory and permitting frameworks, funding opportunities, enabling infrastructure and the availability of storage sites are all elements that comprise the CCUS and BECCUS ecosystem, and they have only recently started to evolve significantly, opening completely new markets dedicated to decarbonisation technologies.

This presents an opportunity to provide the necessary momentum for large-scale deployment of CCUS for environmental purposes. It is initiating a virtuous cycle (and hopefully others will follow) that results in more players in the market, additional technological development, reduced costs and further technological applications. This is exactly what happened in the past with the successful growth of the renewables market, which now accounts for over a third of the global power capacity. The substantial cost reductions of recent decades were largely enabled by the development of the market, also supported by government policies and R&D efforts, resulting in numerous technological breakthroughs (IRENA, 2019).

Policies

National and International polices are paramount to foster the development of decarbonisation markets. Two notable examples of policies are briefly discussed here. Policies and support mechanisms will be covered in more detail in another document currently under development by the AFID Working Group BECCUS.

The first example is the European Union Emissions Trading System (ETS), a market-based mechanism for emission permits for large industrial emitters, launched in 2005. The ETS provides a technology-neutral incentive to reduce emissions by imposing additional costs related to greenhouse gas emissions. The effect of the ETS has been modest at best up to 2020, with annual average European Union Allowance (EUA) values lower than EUR 20/tonne (and lower than EUR 10/tonne in the period 2012-2018). With the announcement of the European Green Deal in 2021 and the progressive reduction of free allowances (up to their complete removal in 2034), the EUA value rapidly increased from around EUR 25/tonne in 2020, to EUR 53/tonne in 2021, and up to the current annual average of around EUR 86/tonne in 2023. The EUA value is expected to further grow in the future. This mechanism creates a business case for that section of industrial emitters, especially in the hard-to-abate sectors, who prefer to invest in decarbonisation technologies instead of continuing to incur the ever-increasing cost of EUAs.

In the United States a different approach has been implemented through a tax incentive programme known as 45Q. Recently further increased in 2022, the 45Q is a performance-based tax credit incentivising carbon capture and sequestration or utilisation, providing differentiated incentives per, geological storage (up to USD 85/tonne) or direct air capture with storage (DACS) (USD 180/tonne). Additionally, the administration has recently announced direct investment to support CCUS projects.

New players for a new market

The CCUS process starts with capturing CO_2 emissions from a wide range of different industrial processes, transporting it along pipelines or via ship, injection into suitable underground formations and monitoring of the storage site for years after the end of the injection phase.

Consequently, the different phases require an extremely wide range of technical competences, from process and chemical engineering, to drilling, geology, geomechanics and so on. Therefore, the emerging CCUS market is characterised by many new players along the entire supply chain.

Emitters are the industrial players that generate emissions and are interested in reducing their CO_2 impact for the reasons listed previously. The capture phase is usually their responsibility, and they require capture technology providers and engineering, procurement and construction contractors to construct the relevant capture plants. The number of technology providers is still limited today, but it is gradually increasing with the growing demand for capture plants and the development of new technologies to improve capture performance and costs.

Transport operators are responsible for the transport of CO_2 from the emitter to the storage/utilisation site, either by pipeline, ship or other means. These usually coincide with storage operators, but the development of CCUS hubs has made it possible for dedicated transport operators to enter the market, and they can also manage intermediate storage sites and logistic hubs.

Finally, there are the storage operators who select, develop and operate CO_2 storage sites. Energy companies form the majority of storage operators because of their upstream heritage, but new operators that specialise in CO_2 storage are emerging on the market.

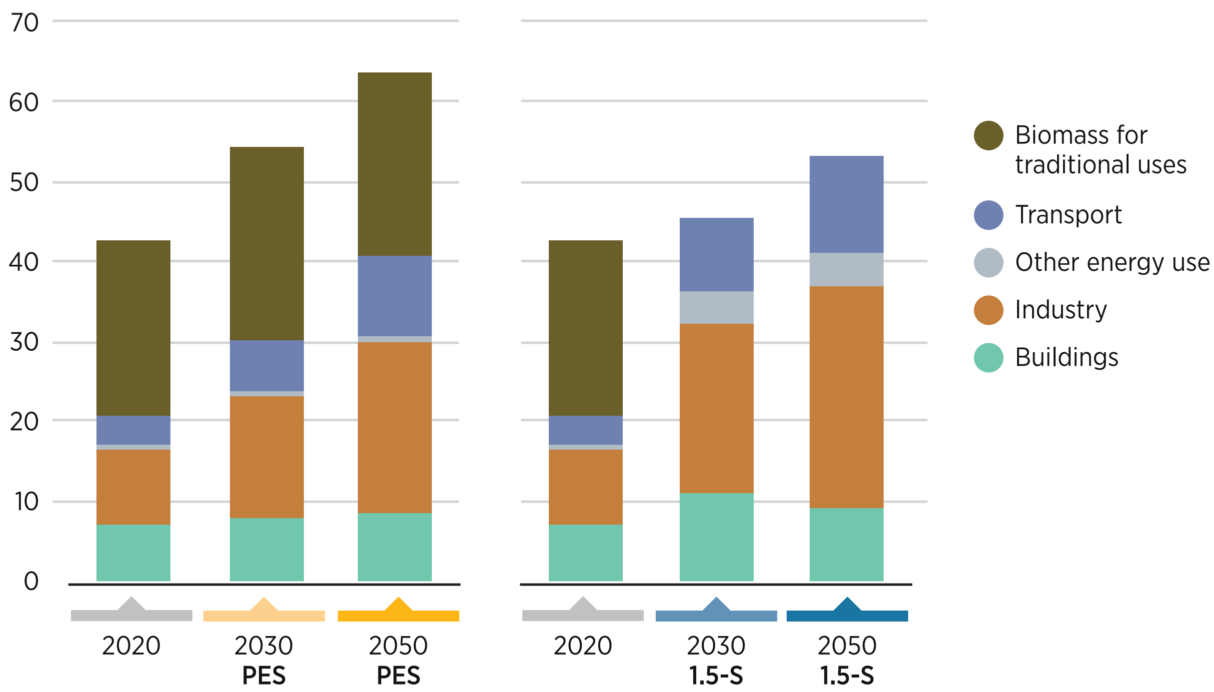
Other opportunities along the CCUS chain can arise for contractors to perform/facilitate specific operations and monitor the safe transport and containment of the CO_2, and organisations to certify process performance throughout the entire production chain are essential.

BECCUS opportunities in the industrial sector

Bioenergy will play a key role in the energy transition. Figure 11 Bioenergy final energy consumption for the PES and the 1.5°C Scenario shows the total final energy consumption (TFEC) for both the Planned Energy Scenario (PES) and 1.5°C Scenario. Notably in 2050, the PES use of bioenergy exceeds the 1.5°C Scenario, largely due to the continued use of "Biomass for traditional uses" (solid biofuels in non-OECD countries). On the other hand, the 1.5°C Scenario shows increased modern bioenergy usage in industry, transport (biofuels in road, aviation and shipping) and other sectors over the PES (IRENA, 2023).

Focusing on the 1.5°C Scenario, the share of primary energy supply of bioenergy in 2050 would grow to 22%. In the same year, the share of modern uses of bioenergy in TFEC would grow to 15% globally. Industry would account for most of this consumption (52%), followed by transport (23%), buildings (18%) and other sectors (8%) (IRENA, 2023).

FIGURE 11 Bioenergy final energy consumption for the PES and the 1.5°C Scenario



Source: (IRENA, 2023).

Notes: PES = planned energy scenario; 1.5-S = IRENA's 1.5°C Scenario.

With the forecast increased usage of bioenergy and the progressive deployment of CCUS as an industrial decarbonisation solution, the prospects for BECCUS will become increasingly promising in the coming years. Currently, the commercial application of BECCUS is very limited. This is largely the result of the current policy climate focusing on emission reduction and not yet incentivising BECCUS. Under the 45Q tax credit in the United States, biogenic CO_2 permanently stored in a geological formation receives a tax credit equivalent to that given to fossil CO_2, without any added incentivisation. In the European Union, BECCUS is not covered under the ETS at the moment. While discussions are in progress to include BECCUS (and DACS), there continues to be no economic motivation for emitters to capture biogenic CO_2 emissions.

Large-scale diffusion of BECCUS is foreseen in the near term, beginning in the United States where the two largest commercial BECCUS facilities are in operation today. The largest push will be in the bioethanol industry, with 69 ethanol projects in the pipeline (GCCSI, 2023). For Europe, waste-to-energy (WtE) appears to be the preferred industry for the deployment of BECCUS, where multiple development projects have already been announced as discussed in the previous section. Existing WtE facilities are numerous throughout Europe and they recover power from municipal waste that naturally contains 40-60% biogenic material, making an appealing target for BECCUS (Becidan, 2021). This is reinforced by the undergoing discussions at European level to include WtE in the ETS.

BECCUS could also play an important role in some industrial sectors, such as biofuels production, paper, cement and steel.

In the biofuels sector, significant growth is expected in the future for the decarbonisation of transport, be it land-based (*e.g.* heavy-duty vehicles), maritime shipping or aviation. In the production of the biofuels, around 20-30% of the overall biomass is attributed to process emissions (DESNZ, 2023), which can be captured using BECCUS. Bioethanol, in particular, is a potential early source of negative emissions, as CO_2 resulting from fermentation processes can be easily captured.

The paper industry produces around 2.5 tonnes of mostly biogenic CO_2 for each tonne of dry pulp. Current global CO_2 emissions from the paper industry are around 350 $MtCO_2$/yr. Standard post-combustion capture of the flue gases could be retrofitted without altering the process. Additionally, waste heat is usually available in paper mills leading to the opportunity of a cost-effective implementation of carbon capture and BECCUS (IEABioenergy, 2020).

Cement currently uses around 6% biomass (such as wood waste and other waste from agriculture and forest processes) for process heat (IEABioenergy, 2020). There is the possibility to fire the kiln up to a recommended value of around 20% biomass (Cavalett and Cherubini, 2021). Additional fuel switching with other biofuels (such as biomethane) could achieve further emission reductions.

In the steel industry, wood-based charcoal is only being used in small blast furnaces in Brazil. For future decarbonisation opportunities with bioenergy, biochar could potentially replace coal used for pulverised coal injection (PCI) in blast furnaces and coke breeze in sintering. Biogas could substitute natural gas in heating furnaces for direct reduced iron (DRI) production (Ekdahl, 2023).

For industry in general, many processes can apply fuel switching to biomethane. Currently the availability of this energy vector is limited, but there is strong market demand as it allows industrial activities to be decarbonised with limited modifications to the process, or none at all. As a consequence, primary energy supply from gaseous biofuel feedstock is expected to increase from 3.3 exajoules (EJ) in 2020 to 13.9 EJ by 2050 (IRENA, 2023). When possible, fuel switching to biomethane allows for BECCUS, with potentially no need for additional retrofitting if CCS is already present.

The technology and operation of CCS and BECCUS are virtually the same regarding CO_2 capture. With increased availability of sustainable bioenergy feedstock, a facility running on fossil energy with CCUS can be upgraded to a BECCUS facility by fuel switching (*e.g.* natural gas to biomethane or coal to biomass) using the existing capture technology. By introducing CCUS and fuel switching in a stepwise approach (notwithstanding the order), hard-to-abate industries will be able to reduce their emissions and potentially achieve negative emissions using BECCUS.

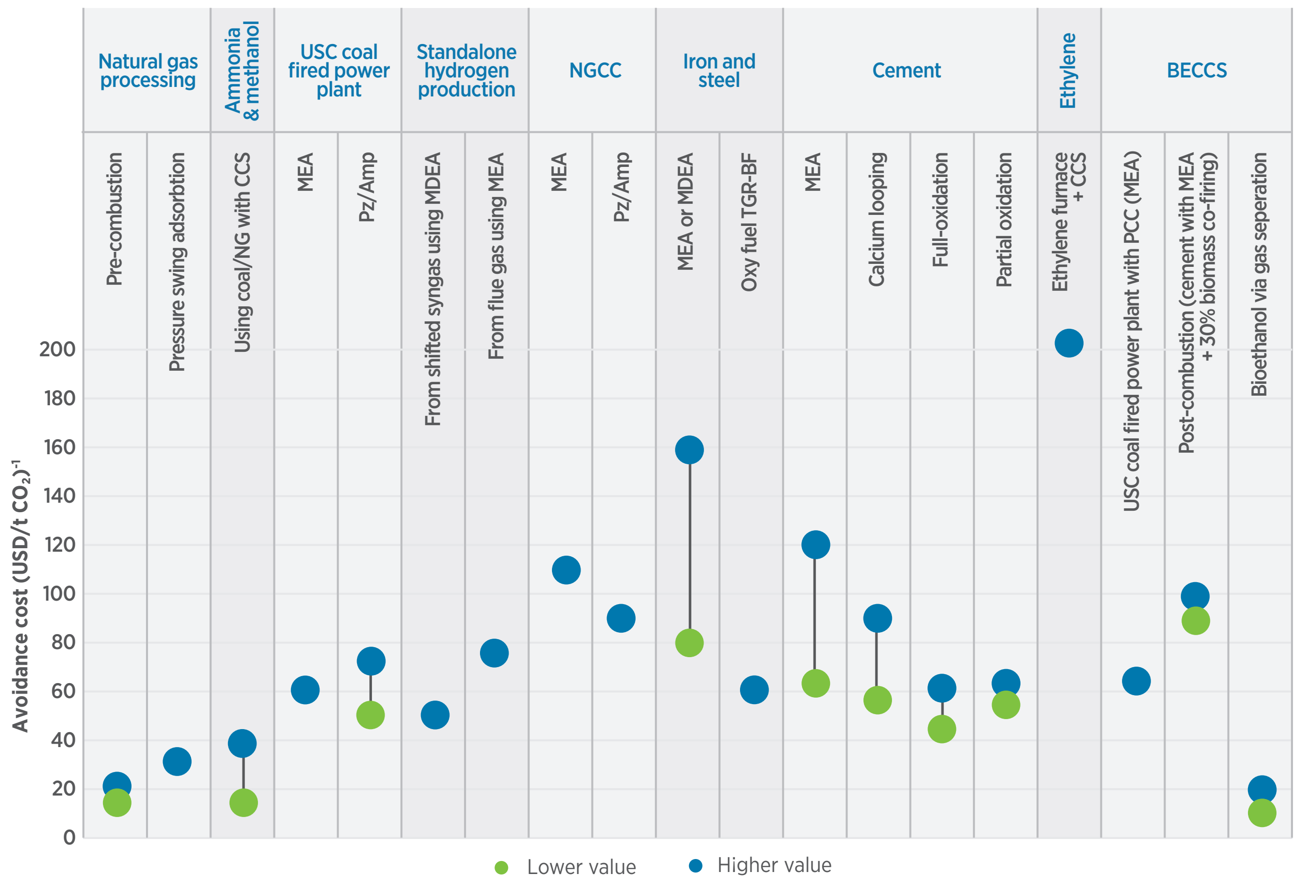
06 The cost of decarbonisation using CCUS and BECCUS

Carbon capture, utilisation and storage (CCUS) projects comprise multiple steps, each having their own associated costs. These costs relate to capture, transport and storage. In addition, for bioenergy with CCUS (BECCUS) there is the incremental cost of switching from fossil fuels to bioenergy. The cost of avoiding CO_2 emission with CCUS and BECCUS technology covers a wide range of values. It spans USD 22-225/t CO_2, depending on several factors such as the specific industrial sector, concentration of CO_2 to be captured, capture technologies utilised, distance from the storage location, and the type of storage.

Generally, the cost of CO_2 capture is the most significant, constituting about 60-70% of the total CCUS chain. Capture costs generally increase as the concentration of CO_2 decreases in the stream to be treated. As such, the highest costs are associated with direct air capture with storage (DACS) as the CO_2 concentration in the atmosphere is extremely low, at only around 418 ppm in 2023.

CO_2 transport can represent a significant share of total CCUS costs and is influenced by the mode of transport (onshore and offshore pipelines, ships, trucks and rail) and other factors such as the need for compression or liquefaction, or the distance of transport.

FIGURE 12: Avoidance costs of CO_2 capture for selected capture technologies



Source: (IRENA, 2021).

Notes: MDEA = methyldiethanolamine; MEA = monoethanolamine; NG = natural gas; NGCC = natural gas combined cycle; PCC= post-combustion capture; TGR-BF = top gas recycled blast furnace; USC = ultra-supercritical; AMP = 2-amino-2-methyl-1-propanol; Pz = piperazine; CCS = carbon capture and storage.

The cost of CCUS and BECCUS also depend on the source of the CO_2. Table 1 provides a compilation of estimated cost range for the full chain process in selected sectors (IRENA, 2021). As shown, costs can vary widely, with the concentration of the CO_2 being one of the most determinate factors.

TABLE 1 Full-chain CCUS/BECCS costs for selected sectors

	Full chain cost (USD/tonne CO_2)	
CCUS	**Low estimate**	**High estimate**
Ammonia/methanol production	22	62
Natural gas processing	31	49
Cement	62	102
Blue hydrogen	73	88
Steel	75	131
Ethylene production	212	225
BECCUS		
Power plant co-fired with biomass	69	85
Cement co-fired with biomass	76	105

Source: (IRENA, 2021).

There is an emergent CCUS market with multiple players, and the investments being made include funding for research and new developments and initiatives. All of which contributes to the future lowering of costs associated with CCUS projects. Even today, the cost of CCUS is already competitive for the decarbonisation of the industrial sector compared with the available alternatives. An example would be the results of the Netherlands' incentive SDE++ programme in 2020 (SDE++, 2021) and 2022 (SDE++, 2023). Funds in this programme are allocated on a competitive basis. CCUS technology emerged as the most effective for emissions reduction and, at the same time, the second most competitive solution in both years on the basis of the cost to the taxpayer per tonne of emissions avoided.

07 Case studies[1]

Carbon capture, utilisation and storage (CCUS) projects worldwide are moving forward and accelerating at a rapid pace. This section discusses some of the current projects being delivered by Eni and Gulf Cryo.

CCUS at Eni

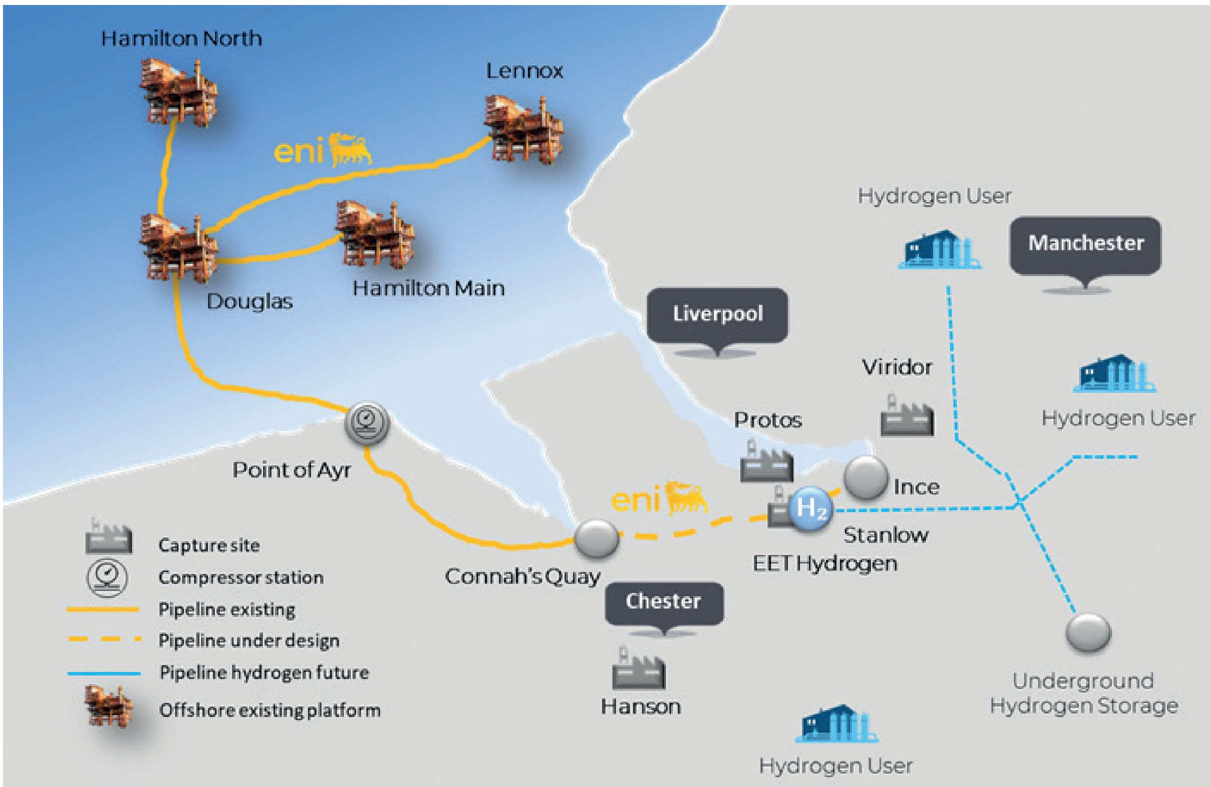
Decarbonisation efforts at Eni include a dedicated CCUS division, including carbon dioxide removal (CDR). Currently, the focus is on transport and storage in depleted oil and gas reservoirs and includes three CCUS hubs: Ravenna CCS (Italy), HyNet North West (United Kingdom) and Bacton Thames Net Zero (United Kingdom). These hubs will cover industrial emissions along with CDR (*e.g.* bioenergy with CCUS [BECCUS] from waste-to-energy plants). Other hubs and CCS projects are under evaluation both in Europe and in other regions.

Ravenna CCS represents a decarbonisation opportunity for the Italian industrial system and a potential reference CCUS hub for Southern Europe and the Mediterranean. With start-up planned for 2026, the initial capacity will be 4 $MtCO_2$/yr with a future expandability to 25 $MtCO_2$/yr. The Bacton Thames Net Zero project, on the east coast of the United Kingdom, received a carbon storage licence from the UK government in August 2023. Start-up is planned for 2027 with a storage capacity of 4 $MtCO_2$/yr, potentially increasing to 10 $MtCO_2$/yr after 2030. A more detailed case study follows, detailing the HyNet North West project.

HyNet North West (United Kingdom)

The HyNet North West project envisages the transformation of one of the United Kingdom's most energy-intensive industrial districts (the Liverpool Bay area on the north-west coast) into one of the world's first low-carbon industrial clusters (Figure 13 Overview of the HyNet North West project). The initial phase is based on hydrogen production from natural gas, including a new hydrogen pipeline. It will supply hydrogen to participating energy-intensive industrial gas users to achieve a significant reduction in their CO_2 emissions.

FIGURE 13 Overview of the HyNet North West project



Source: (ENI, 2023).

[1] *Data presented in this section is accurate as of Q4 2023.*

CCUS will be a key element. The project will take advantage of the conversion of existing Eni infrastructure to store CO_2 emitted from industries in north-west England and northern Wales in the offshore fields of Hamilton Main, Hamilton North and Lennox. Eni obtained a CO_2 storage licence in October 2020 from the UK authorities. The start of storage operations is expected in 2027 with an initial capacity of 4.5 $MtCO_2$/yr. There is a planned expansion programme of up to 10 $MtCO_2$/yr from 2030. This is equivalent to 25% of regional emissions, equivalent to heating over 5 million households.

Overall, the Hynet project will provide a significant contribution to the British CCUS-related emission reduction target of 20-30 Mt/yr. In addition, low-emission hydrogen production will cover 40% of the government's 2030 target of 10 GW, driving the development of the hydrogen economy in the area.

To secure the available CO_2 for injection, Eni UK has signed a total of 21 memorandums of understanding with future emitters, could including cement manufacturers, hydrogen producers and waste-to-energy plants, along with industries such as bioenergy and fertilisers.

In March 2023 the UK government announced the UK cluster sequencing process (Phase 2, Track 1) with five selected emitters. This includes hard-to-abate industries (cement/lime production from Hanson and Tarmac), waste-to-energy plants (Protos and Viridor), and hydrogen production by Vertex Hydrogen.

The HyNet North West project will have an important socio-economic value for the region and United Kingdom in general because it will allow existing jobs to be protected in hard-to-abate sectors, while promoting a more sustainable approach to heavy industry and creating totally new highly skilled supply chains for decarbonisation technologies and services.

CCUS at Gulf Cryo: The introduction and expansion of CCU in the Middle East

Gulf Cryo is a regional leader in industrial, medical and specialty gas solutions, operating across 10 Middle Eastern countries. Dealing with gases for 70 years, the company has a strategic focus on the complete "clean" CO_2 value chain from capture to treatment, distribution and utilisation.

The company inaugurated the first carbon capture plant in the region in 2014. Gulf Cryo has been since developing carbon capture initiatives and building its expertise in innovative utilisation applications.

This case study presents an example of carbon capture adoption within a business model. It also tackles the types of emission sources, as well as the importance of utilisation and its applications.

Equate project – 350 $MtCO_2$/day plant (Kuwait)

Gulf Cryo designed built and operated the first carbon capture facility in the region as early as 2014, a year earlier than Paris Agreement. As CO_2 has always been a core product at Gulf Cryo, the company quickly understood the rationale behind carbon capture, before the term became a focus of governments and a key solution for climate change.

The project aimed to capture and repurpose the CO_2 emissions of Equate in Kuwait. Established in 1995, Equate is a global producer of petrochemicals and the second-largest producer of ethylene glycol in the world.

The carbon capture facility was built at Equate's plant in the Shuaiba Industrial Area. The facility started with a capture capacity of 150 $MtCO_2$/day at inauguration and has ramped up its volume to 350 $MtCO_2$/day by 2022. The aim of Gulf Cryo's operational model is to recover, refine and liquefy raw gases to produce food-grade certified CO_2. An advanced online analyser provides real-time monitoring of CO_2 product quality during treatment, storing and distribution.

The project supports both companies' sustainability roadmaps. It helps Equate decarbonise its operations and allows Gulf Cryo to reuse the recovered CO_2 as a better sustainable solution compared to fossil fuel-derived CO_2.

After the successful operation of the first CCU project in the Middle East and with an increasing demand for clean CO_2 and sustainable solutions, in 2022, Gulf Cryo signed two major deals for carbon capture and utilisation.

Petro Rabigh carbon capture project – 300 $MtCO_2$/day plant (Saudi Arabia)

Gulf Cryo signed a 20-year carbon capture agreement with Petro Rabigh in 2022. Petro Rabigh is one of the world's largest integrated refining and petrochemical facilities. It was founded in 2005 as a joint venture between Saudi Aramco and Sumitomo Chemical.

The collaboration aims to capture CO_2 emissions from the mono-ethylene glycol plant, which is located at the Rabigh Petrochemical cluster in Saudi Arabia and has a capacity of 600 000 tonnes/year.

Gulf Cryo's role is to fund, build, own and operate the carbon capture facility, which became operational in December 2023, capturing in the first stage 300 $MtCO_2$/day emissions. The clean CO_2 is being reused in several industrial applications, creating a domestic circular carbon economy and increasing localisation in line with Saudi Arabia's Vision 2030.

Part of the total captured and purified food grade gas with a total volume of 100 000 tonnes/year will be supplied via pipeline tor internal processes of Petro Rabigh, and the remaining majority will be supplied in liquid form to industrial end users, for use in innovative gas applications in e-fuels, desalination, food and beverage, cement and agriculture.

Ma'aden CC project – 900 $MtCO_2$/day plant (Saudi Arabia)

During the COP27 event in Egypt in November 2022, at the Saudi Green Initiatives Forum, Gulf Cryo and Ma'aden announced a 20-year agreement for a CCU project to capture the CO_2 emissions from the Ma'aden integrated phosphate complex located in the eastern region of Saudi Arabia. The agreement is considered to be the largest CCU project in the Middle East region. Ma'aden is the largest multi-commodity mining and metals company in the Middle East.

Gulf Cryo intends to construct and operate the mega CO_2 capture plant (raw gas from the ammonia plant) within Maaden's integrated phosphate complex at Ras Al Khair, starting with the capture of 300 $MtCO_2$/day by 2024, extending to 900 $MtCO_2$/day.

This project aims to reducre Ma'aden's CO_2 emissions and strengthen its position as a major global supplier of blue ammonia, while providing a clean CO_2 source that will be distributed, partially to International Maritime Industries (IMI), Saudi Arabia's giant maritime yard located in the same industrial basin in Ras Al Khair, and the remainder for conventional and innovative CO_2 applications elsewhere in the region and the country at large.

These partnerships aim to reduce CO_2 emissions at source while providing a clean CO_2 source. Thus, they create a domestic circular carbon economy, and they support the governments' sustainability and localisation visions for the region.

The importance of utilisation and its applications

Geological sequestration is undoubtedly set to provide the largest form of storage for captured CO_2. Although utilisation is a smaller part of the solution, it is an integral one that can also be expanded with further localised investment.

In the Middle East region, Gulf Cryo has deployed a wide range of applications creating value from and monetising the captured CO_2 waste, such as CO_2 utilisation in the remineralisation process for desalinated water (the major current consumer of fossil fuel-derived CO_2), beverage carbonation, agricultural applications, and many other applications, creating a domestic circular carbon economy and fully supporting local government initiatives for climate action.

In addition, Gulf Cryo has showcased advancements in developing locally innovative carbon applications, such as CO_2 injection in concrete ready-mix, piloting projects in algae production and other developments in the pipeline, by partnering with international technology providers and contributing to developing market scale and stimulating commercial demand for the recovered CO_2 waste.

One key part of the clean CO_2 value chain is the CO_2 logistics. Gulf Cryo has invested in a large dedicated fleet of rolling assets in order to secure a reliable supply chain between its carbon capture plants and the industrial end users all over the region.

The need for business and environmental sustainability

A challenge of sustainability lies in the need to pursue both environmental and financial viability. A shift towards one at the cost of the other is not sustainable; rather, what is needed are innovative approaches that maximise both. In the case of Gulf Cryo, the company was able to build a successful business model that promotes both business and environment, to create viable sustainability.

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